

POSSIBLE $d + id$ SCENARIO IN $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ BY POINT-CONTACT MEASUREMENTS

D. DAGHERO, R.S. GONNELLI, G.A. UMMARINO

*Dipartimento di Fisica, Politecnico di Torino
Corso Duca degli Abruzzi 24, 10129 Torino (TO)
E-mail: gonnelli@polito.it*

V.A. STEPANOV

*Lebedev Physical Institute, Russian Academy of Sciences
Leninski Pr. 53, 119991 Moscow, Russia*

We analyze the results of point-contact measurements in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO) previously reported as a clear evidence of the separation between gap and pseudo-gap in this copper oxide. Here we show that, in addition to this, the conductance curves of our point-contact junctions – showing clear Andreev reflection features – can be interpreted as supporting a nodeless $d_{x^2-y^2} + id_{xy}$ -wave symmetry of the gap in LSCO. The results of our analysis, in particular the doping dependence of the subdominant d_{xy} gap component, are discussed and compared to the predictions of different theoretical models.

1 Introduction

In spite of the large number of experimental evidences and theoretical arguments supporting a pure $d_{x^2-y^2}$ symmetry of the order parameter in cuprates^{1,2}, the possible existence of a subdominant component with different symmetry has also been deeply investigated. One of the reasons is that most of the experimental probes cannot really exclude the presence of a small additional component. Another reason is that some tunneling experiments along the ab plane of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) have shown a splitting of the zero-bias conductance peak (ZBCP) both in the presence^{3,4,5,6} and in the absence^{3,4,7} of a magnetic field. A possible explanation of this phenomenon stems from the idea that the ZBCP is due to zero-energy Andreev bound states at the surface^{8,9} that experience a Doppler-like shift to finite energy in the presence of supercurrents. In the absence of a magnetic field, such a shift might be due to spontaneous supercurrents due to the breaking of the time-reversal symmetry. According to Fögelstrom *et al.*¹⁰ a subdominant pairing interaction with smaller critical temperature can in fact appear at the surface of a d -wave superconductor, with a phase shift of $\pi/2$ with respect to the dominant one. This gives rise to spontaneous supercurrents and to a local breaking of the time-reversal symmetry.

An alternative picture has been emerging in the last years, in which an intrinsic instability of the d -wave superconductor toward a time-reversal breaking state is supposed, with no relation to surface effects. This picture is somehow based on the indications of a quantum critical point (QCP) in the proximity of optimal doping, obtained in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (BSCCO) by ARPES¹¹. The hypothesis has been made that such a quantum critical point could mark the transition from a pure d -wave superconducting state to a time-reversal symmetry breaking state, such as $d_{x^2-y^2} \pm is$ or $d_{x^2-y^2} \pm id_{xy}$ ^{12,13,14,15}. Recent tunneling data in YBCO at different

doping levels⁴ have given some support to this second point of view, showing that the spontaneous splitting of the ZBCP only occurs above optimum doping.

In the present paper, we present a possible indication of a $d + id$ scenario in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ (LSCO) obtained by (re)analyzing the results of point-contact measurements in polycrystalline LSCO samples with various doping contents. These data were already reported in a previous paper¹⁶ in a rather different groundwork, i.e. they were shown to evidence the separation between superconducting gap and pseudogap in underdoped LSCO.

2 Experimental details

We used $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$ polycrystalline samples with various doping contents from strongly underdoped to slightly overdoped: $x = 0.08, 0.10, 0.12, 0.13, 0.15$ and 0.20 . Details about the sample preparation and characterization are given elsewhere^{16,17}. The critical temperatures, determined by means of magnetic (a.c. susceptibility) and transport (resistivity) measurements, resulted in good agreement with the standard T_c vs x curve for LSCO¹⁸.

Point contacts were obtained by gently pressing sharp Au tips (whose ending-part diameter was always less than $\sim 2 \mu\text{m}$) against the surface of the samples. We often obtained SN junctions with clear Andreev reflection characteristics. In some cases, the stability of the point contacts allowed us to follow the evolution of the conductance curves on heating the junction from 4.2 K up to the temperature T_c^A at which the dynamic conductance dI/dV was flat.

A discussion of the regime of current flow through our point contacts was already reported elsewhere¹⁶. Here let us just remind that we systematically rejected all the data sets showing an anomalous temperature and voltage dependence of the normal-state conductance (for example, for $V > 20$ mV) that usually indicate the presence of heating effects in the junction¹⁹. As a result, all the curves that have been used for the following analysis can reasonably be thought of as obtained in a regime of ballistic current flow through the junction, thus allowing us to perform spectroscopic measurements with a good energy resolution (< 1 meV).

3 Results and discussion

Fig. 1 reports the experimental conductance curves at low temperature ($4.2 \div 5.6$ K) for all the aforementioned doping contents, normalized to the normal-state conductance – so that they tend to unity at high positive (negative) voltage. The curves have been shifted vertically for clarity. Solid lines represent the best-fitting theoretical curves calculated by using the BTK model²⁰ generalized by Tanaka and Kashiwaya^{9,21} with a $d_{x^2-y^2} + id_{xy}$ symmetry of the order parameter. The details of the fitting procedure are reported elsewhere¹⁷. The fitting parameters are $\Delta_{x^2-y^2}$ and Δ_{xy} , Z (related to the height of the potential barrier) and the broadening parameter Γ that was always kept as small as possible.

Even at a first glance, the fit appears rather good. Notice that the “dip” present in some curves, which is a fairly typical feature, cannot be fitted at all by the model, irrespective of the gap symmetry used. It must be said here that, as pre-

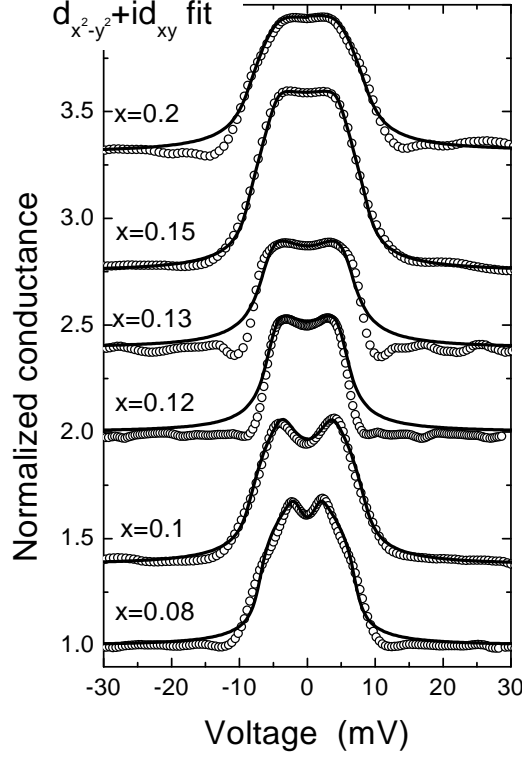


Figure 1. Fit of the conductance curves obtained at low temperature ($4.2 \div 5.6$ K) in samples with different doping levels. The value of the Sr content, x , is indicated near each curve. Symbols: experimental data; solid lines: best-fitting curves.

viously reported¹⁶, various other symmetries were tried: s , d , $s + id$, *extended* s and *anisotropic* s , and none of these could give good results, especially when the temperature evolution of the curves was considered. Only the $s + d$ symmetry was found to fit almost equally well the experimental data^a, but its compatibility with the symmetry of the LSCO lattice at these doping levels is questionable^{1,22}.

The fit of the low-temperature conductance curves shown in Fig. 1 gives the doping dependence of the low-temperature gap components, $\Delta_{x^2-y^2}$ and Δ_{xy} , reported in Fig. 2 (solid circles and squares, respectively). The error affecting each gap value is rather small (about the size of the points)^b. The amplitude of the gap, $|\Delta| = \sqrt{\Delta_{x^2-y^2}^2 + \Delta_{xy}^2}$ is also shown (solid triangles). It is clearly seen that the d_{xy} component is present for all doping levels and is always smaller than the $d_{x^2-y^2}$ one – though representing a substantial part of the total amplitude. Neither $\Delta_{x^2-y^2}$ nor Δ_{xy} increase monotonically with decreasing doping, as instead do both

^a Actually, for some doping values (e.g. $x = 0.08$, $x = 0.15$) the $d + id$ fit is considerably better.

^b Although there are 4 fitting parameters, changing each of the gaps has a very different effect on the curve, and thus the allowed range of gap values is smaller than expected.

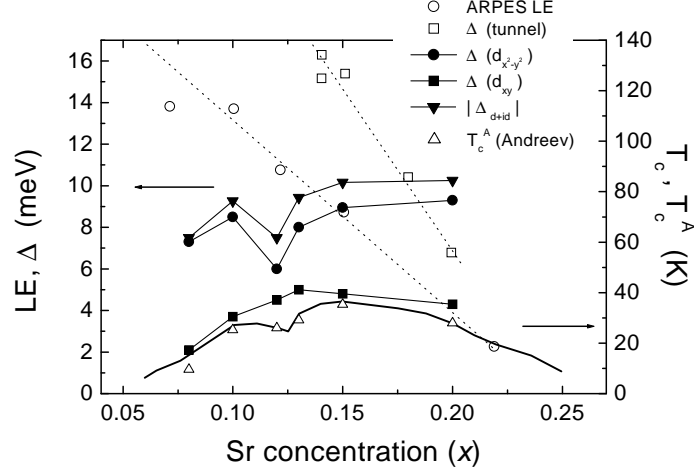


Figure 2. Doping dependence of the gap components and of the gap amplitude, obtained from the fit of the curves in Fig. 1. A comparison is made with the results of tunnel and ARPES measurements (from refs.[23] and [24], respectively), and with the standard T_c vs x curve (from ref. [18]) .

the tunneling gap (open squares) and the ARPES leading-edge shift (open circles). Rather, a decreasing tendency is evident in the underdoped region. A comparison is also made with the standard curve of T_c versus doping (thick solid line)¹⁸, which is strikingly similar to the $\Delta_{xy}(x)$ curve and, with less accuracy, to the $|\Delta|(x)$ one. Notice that a strong suppression of both $\Delta_{x^2-y^2}$ and $|\Delta|$ occurs at $x = 1/8$, where also T_c is reduced, further indicating a close relationship between the Andreev gap and the critical temperature. Thus, the conclusion holds true that we drew in a previous paper¹⁶: Andreev reflection does measure the superconducting gap, as opposed to ARPES and tunnel spectroscopies that instead measure the pseudogap.

Further support to this assertion comes from the temperature dependence of the conductance curves of our junctions. In all cases, in fact, the Andreev-reflection features disappear at a temperature T_c^A close to or smaller than the bulk critical temperature measured by resistivity, with no evidence of persistence of the gap above T_c . The values of T_c^A are reported for each doping level in Fig. 2 (open triangles). Fig. 3 shows, as an example, the temperature evolution of the curve for $x = 0.20$ already shown in Fig. 1, together with the $d + id$ best-fitting curves obtained by keeping Z constant ($Z = 0.135$, which is the value at 4.2 K).

Fitting the normalized conductance curves at all temperatures allows us to obtain the temperature dependence of the two gap components, which is shown for the case $x = 0.20$ in Fig. 4. It is clearly seen that the d_{xy} component is always smaller than the $d_{x^2-y^2}$ one, and that the thermal evolution of both components follows a very similar trend, rather different from a BCS curve. Notice that the critical temperature T_{c2} of the subdominant d_{xy} component is smaller than T_c . A very similar thermal evolution of the gap components is observed also for the remaining doping levels. Further details will be given in a more extended paper.

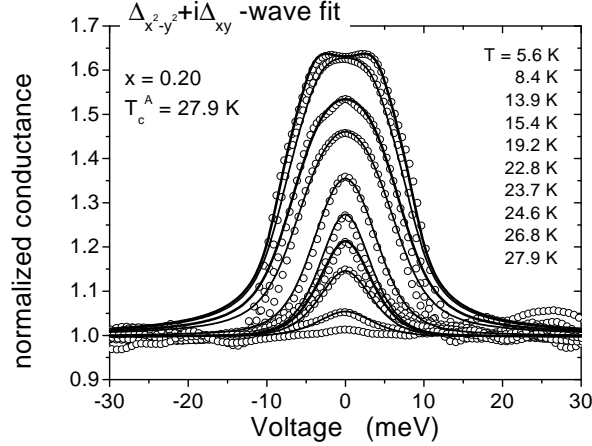


Figure 3. Experimental normalized conductance curve (symbols) obtained in slightly overdoped LSCO at various temperatures, from 4.2 K up to the temperature T_c^A at which the Andreev-reflection feature disappear together with their best-fitting curves (lines) calculated by using the generalized BTK model with $d + id$ pairing.

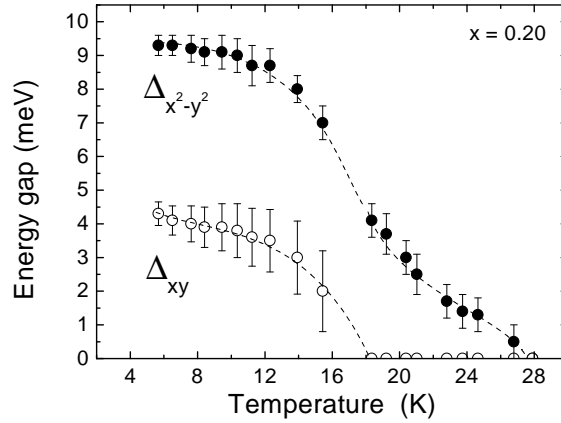


Figure 4. Dependence of the dominant ($d_{x^2-y^2}$) and subdominant (d_{xy}) gap components on the temperature, obtained from the fit of the conductance curves shown in fig.3. Error bars indicate the range of values that give an acceptable fit when the remaining parameters are suitably adjusted (note that Z was fixed to its low- T value). Dashed lines are guides to the eye. It is well clear that the d_{xy} component closes at a lower temperature. The same happens at all doping contents.

4 Conclusions

As far as the gap symmetry is concerned, our findings agree with some tunneling measurements in optimally-doped LSCO, that evidenced the absence of nodes in the gap²⁵ and also with previous Andreev reflection experiments²⁶ that were interpreted as supporting a mixed symmetry. Of course, the question whether the additional d_{xy} component arises from surface effects or from a quantum phase transition cannot be addressed by our measurements. However, it must be said that the presence of the subdominant d_{xy} pairing in the *whole* doping range analyzed, as well

as its dependence on the doping (see Fig. 2) disagree with the findings in YBCO films⁴. In that case, the spontaneous splitting of the zero bias in the tunneling conductance (proportional to the amplitude of the d_{xy} component) was observed only above optimal doping, and turned out to increase monotonically with increasing doping. This behaviour was indeed used to argue for a quantum critical point near optimal doping, and was reproduced by some theoretical models predicting the stability of the $d + id$ phase in the overdoped regime^{14,15}. What our results say, instead, is that either the time-reversal symmetry breaking is a surface effect with no relationship to quantum criticality¹⁰ (and perhaps related to doping only through the amplitude of the dominant gap component), or the quantum critical point is placed somewhere in the extreme underdoped or extreme overdoped region of the phase diagram. Further measurements in these two extreme regimes will possibly help in discriminating between these two possibilities.

V.A.S. acknowledges the support from RFBR (project N. 02-02-17133).

References

1. C.C. Tsuei and J.R. Kirtley, Rev. Mod. Phys. **72**, 969 (2000).
2. B. Brandow, Phys. Rep. **296**, 1 (1998).
3. M. Covington *et al.*, Phys. Rev. Lett. **79**, 277 (1997).
4. Y. Dagan and G. Deutscher, Phys. Rev. Lett. **87**, 177004-1 (2001).
5. M. Aprili, E. Badica, and L.H. Greene, Phys. Rev. Lett. **83**, 4630 (1999).
6. R. Krupke and G. Deutscher, Phys. Rev. Lett. **83**, 4634 (1999).
7. J. Geerk, X.X. Xi, and G. Linker, Z. Phys. B **73**, 329 (1988).
8. C.-R. Hu, Phys. Rev. Lett. **72**, 1526 (1994).
9. Y. Tanaka and S. Kashiwaya, Phys. Rev. Lett. **74**, 3451 (1995).
10. M. Fögelstrom, D. Rainer, and A. Sauls, Phys. Rev. Lett. **79**, 281 (1997).
11. T. Valla *et al.*, Science **285**, 2110 (1999).
12. M. Vojta, Y. Zhang, and S. Sachdev, Phys. Rev. Lett. **85**, 4940 (2000).
13. D.V. Khveshchenko and J. Paaske, Phys. Rev. Lett. **86**, 4672 (2001).
14. S. Sachdev, cond-mat/0109419.
15. G. Sangiovanni *et al.*, cond-mat/0111107.
16. R.S. Gonnelli *et al.*, Eur. Phys. J. B **22**, 411 (2001).
17. R.S. Gonnelli *et al.*, Int. J. Mod. Phys. **14**, 3472 (2000).
18. H. Takagi *et al.*, Phys. Rev. B **40**, 2254 (1989).
19. A.G.M. Jansen *et al.*, J. Phys. C: Solid St. Phys. **13**, 6073 (1980); Yu V. Sharvin and N.I. Bogatina, Sov. Phys. JETP **29**, 419 (1969).
20. G.E. Blonder, M. Tinkham and T.M. Klapwijk, Phys. Rev B **25**, 4515 (1982).
21. S. Kashiwaya *et al.*, Phys. Rev. B **53**, 2267 (1996); S. Kashiwaya and Y. Tanaka, Rep. Prog. Phys. **63** 1641 (2000).
22. R.A. Klemm, C.T. Rieck and K. Scharnberg, Phys. Rev. B **61**, 5913 (2000).
23. N. Momono *et al.*, Physica C 317-318, 603 (1999).
24. A. Ino *et al.*, cond-mat/0005370 (2000).
25. T. Ekino *et al.*, Physica C **263**, 249 (1996).
26. N.S. Achsaff *et al.*, J. Low Temp. Phys. **105**, 329 (1996).